JOINT INVENTORS

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EL564459915US.
Date of Deposit: April 5, 2001
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APPLICATION FOR
UNITED STATES LETTERS PATENT

S P E C I F I C A T I O N

TO ALL WHOM IT MAY CONCERN:

Be it known that we, Thomas Eliott Lee, a citizen of the United States, residing at 8403 Pebble Cove Ct., Apartment D, Bakersfield, California, and Inchan Choi, a citizen of the United States, residing at 1449 Yale Ct., Naperville, Illinois, and Byoung In Suh, a citizen of the United States, residing at 8 Hamilton Lane, Oakbrook, Illinois, have invented a new and useful IMAGE BASED VOLUMETRIC MEASURING DEVICE, of which the following is a specification.

IMAGE BASED VOLUMETRIC MEASURING DEVICE

FIELD OF THE INVENTION

The invention generally relates to measuring devices and, more particularly, relates to devices and methods for measuring sample volumes and changes in sample volumes.

BACKGROUND OF THE INVENTION

Many fields use adhesives, glues, and plastics which must be cured before setting. The curing process often results in shrinkage of the material, which in turn causes stresses to arise within the material and the substrate to which the material is bonded.

For example, in the field of dentistry, dental restoration procedures often require various resin-containing materials, such as composites and adhesives, to be filled into a tooth cavity or area being repaired. The material is then cured using a hand tool which emits light through a bundle of optic fibers to result in a focused light output. The material is cured by polymerization resulting from the light exposure.

However, shrinkage of the restorative material used to fill the cavity can create stresses which may lead to premature failure or otherwise necessitate repair. Development of adhesives and polymers which undergo less volumetric change, or development of curing methods which relieve stress, are therefore advantageous in the development of new storage

materials. A key to the development of such materials is the ability to measure small changes in volume. Present methods used to measure volumetric changes include water or mercury dilatometers, or methods which measure a change in one dimension and try to deduce volumetric change therefrom.

Water and mercury dilatometry operate by measuring the amount of water or mercury which is displaced by the sample volume within a sample chamber. The volume of mercury or water is determined by weighing the displaced water or mercury. The accuracy of these techniques and instruments require precisely controlling temperature, precisely controlling the chamber volume from which the water or mercury are displaced, and precisely weighing the displaced mercury or water. Errors can be introduced into the measuring process at any or all of the steps. In addition, such instruments are time consuming to use and, due to the many steps required to obtain a measurement, can suffer from operator bias. Sample interactions between the displacement fluid and the sample can also affect accuracy. For example, polymers used for restorative dentistry may absorb water and may expand as a result. Also, due to the time consuming nature of each measurement, the number of measurements which can be practically made by a researcher is limited.

Controlling the manner in which the curing process is conducted may also relieve stresses within the material boundaries. For example, the manner in which light is applied to light-cured restorative materials in dentistry may relieve the stress between the adhesive and the tooth. Testing this

hypothesis, however, requires an instrument which can reveal not only the amount of volume change, but also the location or locations at which the sample volume has changed. It would also be helpful to know the portion of the sample which changed volume first.

SUMMARY OF THE INVENTION

In accordance with one aspect of the invention, a measuring device is provided which comprises a camera adapted to generate images of an item being measured, and a processor operatively associated with the camera and adapted to calculate the volume of the item based on the generated images.

In accordance with another aspect of the invention, a volumetric measuring device is provided which comprises a platform, a camera, a processor, and a display device. The platform is adapted to support an item to be measured and is rotatable in increments across a 360° range of rotation. The camera is positioned proximate the platform and is adapted to generate images of the item. The processor is operatively associated with the camera and is adapted to identify outlines of the item in each image and calculate the volume of the item. The volume is calculated by calculating a volume associated with each image and adding the volumes associated with each of the images. The display device is operatively associated with the processor and is adapted to display the information associated with the calculated volume.

In accordance with another aspect of the invention, a method of calculating a volume of a sample is provided comprising the steps of

recording camera images of the sample from N angles where the N angles total 360 degrees, digitizing the images, identifying an outline of the sample, dividing the image into a plurality of parallel slices, tabulating the height and width of each slice, calculating the volume associated with each slice, and summing the calculated volumes associated with each slice for each of the N images.

According to another aspect of the invention, a method of calculating a volume of a sample is provided comprising the steps of recording a camera image of the sample, tabulating a volume associated with the image, and calculating the volume of the sample based on the tabulated volume associated with the image.

These and other aspects and features of the invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic representation of a measuring device constructed in accordance with the teachings of the invention;

FIG. 2 is a schematic representation of a sample divided into a plurality of slices in accordance with the teachings of the invention;

FIG. 3 is an isometric view of a single slice according to FIG. 2;

FIG. 4 is an isometric view of a portion of the slice of FIG. 3 which may be generated from a single image taken by a measuring device constructed in accordance with the teachings of the invention;

FIG. 5 is a sample outline depicted on a partial pixel grid according to the teachings of the invention; and

FIG. 6 is a flow chart depicting a series of steps which may be taken by a measuring device constructed in accordance with the teachings of the invention.

While the invention is susceptible to various modifications and alternative constructions, certain illustrative embodiments thereof have been shown in the drawings and will be described below in detail. It should be understood, however, that there is no intention to limit the invention to the specific forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions and equivalents falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, and with specific reference to FIG. 1, a measuring device or system constructed in accordance with the teachings of the invention is generally referred to by reference numeral 20. While the device 20 will be described below for use in conjunction with measuring volumetric reductions associated with dental restorative materials upon being cured, it is to be understood that the teachings of the invention can be used in connection with any other type of function wherein accurate measurement of volumes is desirable. Such other functions include, but are not limited to, medical, research, industrial, and construction activities wherein materials subject to shrinkages or other changes in volume may affect function

performance. Moreover, it is to be understood that while the equations and steps discussed herein may be calculated and performed manually, they are preferably encoded into software and calculated by microprocessor.

Referring again to FIG. 1, the device 20 is shown to include a platform 22 upon which a pedestal 24 is positioned. The platform 22 is mounted to a shaft 26 extending from a motor 28. The motor 28 may be provided in the form of a stepper motor, wherein the shaft 26 is adapted to move in uniform increments, or may be provided in the form of a motor and drive arrangement adapted to move the shaft 26 in incremental movements. The motor 28 may also be provided in the form of a servo-motor. One suitable example of the motor 28 is a stepper motor capable of making 3200 micro-steps per shaft revolution.

The pedestal 24 provides a surface 30 upon which a sample 32 may be positioned for measurement. As indicated above, the sample 32 may be provided in the form of a dental restorative material. Positioned proximate the sample 32 is a camera 34, which may be provided in the form of a charge coupled device (CCD) camera. The camera 34 is adapted to record images of the sample 32 at each location to which the shaft 26 and pedestal 24 are rotated. More specifically, if the shaft 26 is adapted to rotate in N increments, which in total sum to 360°, the camera 34 will accordingly record N images. The value of N is preferably adjustable in the software of the system 20 to increase or decrease the accuracy of the calculations as desired. For example, if N is set to four, an image will be recorded at every ninety degrees of revolution. This will allow quick calculations and measurements but, unless

the change in volume is isotropic, will not be as precise as calculations performed wherein N is set to a greater number and a corresponding greater number of images are recorded.

Preferably, the sample 32 is provided within an enclosure or isolation chamber 36 having an operable door 38. One or more light sources 40 are preferably provided within the isolation chamber 36. A black or otherwise opaque background 42 are also provided within the isolation chamber 36. The lights 40 are preferably positioned so as to illuminate the sample 32 without illuminating the background 42.

The camera 34 is operatively associated with a processor 44. The processor 44 may be provided as a part of a personal computer 46 or any other type of suitable electronic processing component. An operator interface device 48 is operatively associated with the processor 44 and preferably includes a display screen 50.

Referring now to FIGS. 2-5, the sample 32 is depicted in further detail. The processor 44 receives images 51 from the camera 34, digitizes the data associated with each image 51, and reconstructs the sample 32 into a digitized image 52 displayable upon a pixel grid 54 as shown in FIG. 5. Since the sample 32 is recorded against a black backdrop 42, the intensity of each pixel 56 associated with the sample 32 is identifiable upon the pixel grid 54 by the processor 44. As will be described in further detail herein, this may be accomplished by comparing the intensity of each pixel to a threshold intensity value. The pixel grid 54 may be of various size, such as 640 by 480, or larger, with larger grids 54 necessarily resulting in greater resolution.

In order to calculate the volume of the sample 32, a first step is to divide the outline 58 of the image into a plurality of slices 60. In the depicted embodiment, the slices are provided horizontally and each has a height, h, equal to one pixel. Alternatively, the slices 60 may be provided vertically, wherein each slice has a width of one pixel, or another known, constant value.

As shown best in FIG. 3, each slice 60, in the depicted embodiment, is substantially cylindrical in shape. However, as can be seen from FIG. 4, the portion of each slice or disc 60 which is reconstructed for each image taken by the camera 34 is only a small percentage of the total disc volume. Accordingly, to calculate the volume of a single slice 60, the volume of each portion 62 must first be calculated, and added to the volumes of each additional portion 62 comprising the entire slice 60. According to a multiple view embodiment of the invention, i.e., wherein N is greater than one, the volume of each portion 62 must be calculated for each slice 60 comprising the entire sample 32, and then the slice volumes are added together to generate the volume for the entire sample 32. According to a single view embodiment discussed in further detail herein, the volume for the entire sample 32 can be based on a single view, i.e., N = 1, based on the premise that the sample 32 is symmetrical.

Referring now to FIG. 5, a portion of the pixel grid 54 is shown, with an outline 58 resulting from a single image depicted as well. Before the volume of the sample 32 can be calculated, it is first necessary to account for the volume represented by the pedestal 24. This can be accomplished in at least

two ways. According to a first system, the volume of the pedestal can be calculated before the sample is measured, with the pedestal volume being stored in memory. This requires a calibration step prior to measuring the sample 32 and also requires that the pedestal 24 be cleaned before each use.

An alternative requires that the user identify on the pixel grid the point at which the pedestal 24 stops and the sample 32 begins. This may be accomplished in software by providing an analysis box or icon which may be manipulated on screen by the user. For example, the user may use an input device, such as a mouse, tractor ball, or the like, to display an analysis box on screen. Such an analysis box may be adjustable in size and shape and enable the user to drag the analysis box directly over the sample 32, and only the sample 32. Volume calculations can then be performed for only the image within the analysis box.

Once the pedestal 24 is accounted for, the volume of the image may be calculated. The height of each slice 60 may, as indicated above, be maintained at a constant of one pixel. In order to calculate the width of each slice, the number of pixels 56 comprising the slice 60 must be calculated. This may be accomplished in a number of different ways. One way in which the width can be calculated is by counting the number of pixels 56 above a predetermined threshold of light intensity. Since the backdrop 42 is black or otherwise opaque, the processor 44 can compare the intensity of each pixel 56 within a given slice 60 to the predetermined threshold and if the intensity is greater than the threshold, add the pixel to the total width of the slice 60. In

the depicted example, the slice 60 has a width of ten pixels. The threshold value is preferably adjustable, but should be set at a level to ensure all viable pixels are counted, while minimizing the effect of noise or other extraneous signals.

Alternatively, the width of the slice 60 can be calculated by identifying the left most pixel 64, the right most pixel 65 and using the following equation:

$$w_m = (x_{mR} - x_{mL}) + 1,$$

wherein w_M represents the width of the slice, x_{mR} represents the right most pixel, and x_{mL} represents the left most pixel. The left most pixel 64 of the image may be identified by the processor 44 by starting with the left most side 66 of the pixel grid 54 and moving right until, in comparing the intensity of each pixel 56 to the threshold value, a pixel having an intensity above the threshold value is identified. The right most pixel 65 can then be similarly identified by starting from the right most side 67 of the pixel grid 54 and moving left. This method has the benefit of ensuring that dark regions on the sample 32 are not viewed by the processor 44 as below the threshold value and thus not counted.

Once the height and width of each slice 60 are determined, the total volume of the sample 32 can be calculated. The volume of each slice 60 can be calculated using the following equation:

$$v_s = h \times \prod \times (W_{mn} / 2)^2.$$

However, as stated above, each slice 60 is divided into a number of portions 62, wherein the number of portions comprising each slice

corresponds to the number of images recorded by the camera 34. If N represents the number of images of the sample 32 for each 360° revolution of the sample 32, the volume of N portions must be calculated. The following equation may be used to calculate the volume of each portion 62:

$$v_p = 1 / N \times h \times \prod \times (W_{mn} / 2)^{2}.$$

Once the volume of each portion 62 is known, the volume of the entire sample 32 can be calculated by summing the portions 62 comprising each slice 60, and then summing the volumes of each slice 60. More specifically, the following equation can be used to calculate the total sample volume:

$$v_t = \sum_{n=1}^{N} \sum_{m=1}^{M} 1 / N \times h \times \prod \times (W_{mn} / 2)^{2}.$$

Since a sample may exhibit a different degree of reflectivity, both before and after curing, the system 20 further enables an intensity slope to be calculated and factored into subsequent calculations. The intensity slope may be calculated using the equation:

$$S = \sum_{m=1}^{M} \left(p(m, x_{lt} + 1) - p(m, x_{lt}) + p(m, x_{rt} - 1) - p(m, x_{rt}) \right) / 2 ,$$

where S is the intensity slope, x_{lt} is the first x position from the left side of the pixel grid 54 where the pixel intensity is above the threshold value, and x_{rt} is the first x position from the right side of the pixel grid 54 where the pixel intensity is above the threshold value. A change in the intensity slope can then be calculated for the sample 32 before and after curing and added to subsequent calculations.

The teachings of the invention, can be used to construct a device 20 adapted to calculate not only the volume of a single sample 32, but the volumes for the sample 32 both before and after a change in volume. For example, if the sample 32 is a dental restorative material, adapted to be cured, a light probe may be introduced to cure the sample 32 after the sample 32, in its cured state, is measured. The sample 32 accordingly will decrease in volume. The processor 44 can then calculate the change in volume before and after the curing process using the following equation:

$$\Delta \%v_t = 100 \times (v_1 - v_2) / v_1 ,$$

where v_1 is the volume before the curing process, and v_2 is the volume after the change in volume.

For the situation, alluded to above, where the change in volume occurs by the same amount in all the dimensions of the sample (symmetrical reduction along all three x, y, z coordinates), the percent change in volume can be accurately measured from volumetric reconstructions which are preformed from a single view (N=1). This is because in this special case, the measured volumes (reconstructed from a single view), which are defined herein as v_{m1} (volume measured before the change in volume) and v_{m2} (volume measured after the change in volume), are related to the true volume by the equations:

$$v_{m1} = k \times v_1 , \text{ and}$$

$$v_{m2} = k \times v_2 ,$$

where k is a constant. If the measured volumes v_{m1} and v_{m2} are substituted into the equation for percent change, the following equations are obtained:

$$\Delta\%v = 100 \times (v_{m1} - v_{m2}) / v_{m1}$$, which reduces to

$$\Delta\%v = 100 \times (k \times v_1 - k \times v_2) / (k \times v_1)$$, which reduces to

$$\Delta\%v = 100 \times (v_1 - v_2) / v_1 .$$

It will be noted that the above equation is the same as that obtained using the true volumes v_1 and v_2 disclosed earlier. Measuring the change in volume from a single view has the advantages that change in volume can be measured faster, and methods for displaying the change in volume are easier for the operator to interpret.

Once the volume and change in volume have been calculated, the device 20 is able to display the calculated information to the user using the operator interface device 48. Before and after graphical representations of the sample 32 can be displayed on the display screen 50 in multiple formats, including, but not limited to, simultaneously, or repeatably in alternating fashion. The outlines 58 generated for each sample 32 both before and after the curing event can be used to generate two or three-dimensional images of the sample to provide the operator with useful information not only as to the total volume of the reduction, but the location of the changes as well. The frequency with which the images are alternated can be modified in the software as desired.

Another option for displaying the change in volume utilizes a difference image with pixels j_{xy} using the formula:

$$j_{xy} = \frac{I_{hm}}{I_m}(k_{xy} - i_{xy}) + I_{hm} ,$$

where I_m is the maximum pixel intensity, I_{hm} is half the maximum pixel intensity, i_{xy} are pixel intensities before the change in volume, and k_{xy} are pixel intensities after the change in volume. In other words, the difference image provides a pixel for pixel comparison, or change in state for every pixel of the image.

In operation, the device 20 can be used to calculate the volume of a sample 32, as well as the change in volume in the sample 32. The device 20 can also represent the change in volume to an operator using a display screen 50. Such representation can be numerical, graphical, in the form of two or three dimensional images, or the like.

Referring now to FIG. 6, a sample sequence of steps which may be taken by the device 20 are depicted. It is to be understood that the depicted sequence is by way of example only, and that other possible step sequences are possible and within the scope of the invention. As shown in FIG. 6, a first step 68 may be to prepare a light curable sample polymer 32. For example, approximately 20 microliters of a polymer may be rolled into a ball and placed onto the pedestal 24. The door 38 of the isolation chamber 36 is then closed. A second step 69 then requires that the volume of the pedestal 24 be accounted for using, for example, one of the above calibration or analysis box alternatives.

In a step 70, the camera 34 is used to generate an image from a first side of the sample 32. If the multiple view option is selected, the sample is then rotated N times as indicated by step 72, with a camera image being

taken at each increment of rotation, until the sample 32 has rotated 360°, as indicated by a step 74.

After images have been taken at each increment of revolution, the images are digitized by the processor 44 as indicated by a step 76. The outline 58 of the sample 32 is determined in a step 78 by comparing pixel intensities to a threshold intensity value. The outline 58 is then divided into a plurality of slices 60 having a constant dimension in one direction, for example height, as indicated by step 80. The width of each slice portion 62 is then calculated in a step 82, with the portion volume being calculated in a step 84. The entire slice volume is then calculated in a step 86. The sample volume is then calculated by summing the calculated slice volumes as indicated by a 88. The processor 44 employs the equations identified above to perform the steps 82-88.

Before the calculated values can be assured of being reliable, the sample 32 must be allowed to settle upon the pedestal 24. This may require several minutes while the sample and the temperature within the chamber 36 reach equilibrium. During this time, the sample volume may be continuously reconstructed and monitored as indicated above, but the calculated volume is only utilized once it has been determined that the sample volume has stabilized as indicated in a step 90. A number of different tests can be utilized to determine whether the sample volume is stabilized with one such test being whether the calculated volume has been calculated to be the same value for a sufficiently high number, e.g., three or more, of times.

If the sample volume is not stabilized, the device 20 returns to the image taking step 70 to repeat the process until the sample volume has stabilized. If the sample volume has stabilized, the device 20 determines whether the sample 32 has yet been cured as indicated in a step 92. If the sample 32 has not yet been cured, the calculated volume is recorded as indicated in a step 94 and the sample is then cured as indicated in a step 96. If the sample has already been cured, the calculated volume is recorded as indicated by a step 98. The calculated before and after volumes can then be displayed as indicated by a step 100. The determination whether the sample 32 has been cured can be performed by the operator, or can be prompted by the processor 44, as by displaying a suitable message on the operator interface device 48.

From the foregoing, it will be appreciated that the invention provides a measuring device to calculate the volume of a sample in a quick, repeatable, and accurate manner without exposing the sample to interactions with testing materials. The device also provides a method by which before and after volumes can be not only calculated, but displayed to a user in graphical and/or numerical format.